Chapter 1 Overview

The Nuclear Science Wall Chart has been created to explain to a broad audience the basic concepts of nuclear structure, radioactivity, and nuclear reactions as well as to highlight current areas of research and excitement in the field. This chart follows the example of two very successful wall charts that have been developed earlier by the Contemporary Physics Education Project (CPEP)—one focused on the Standard Model of fundamental particles and another on fusion and plasma physics. New terminology and the physics behind the chart are explained in subsequent chapters and in the glossary.

Nuclear Science is the study of the structure, properties, and interactions of atomic nuclei, which are the hearts of *atom*s. The nucleus is the place where almost all of the mass of ordinary matter resides. Understanding the behavior of nuclear matter under both normal conditions and conditions very far from normal is a major challenge. Extreme conditions existed in the early universe, exist now in the cores of stars, and can be created in the laboratory during collisions between nuclei. Nuclear scientists investigate by measuring the properties, shapes, and decays of nuclei at rest and in collisions. They ask questions such as: Why do the *nucleons* stay in the *nucleus*? What combinations of *protons* and *neutrons* are possible? What happens when nuclei are squeezed? What is the origin of the nuclei

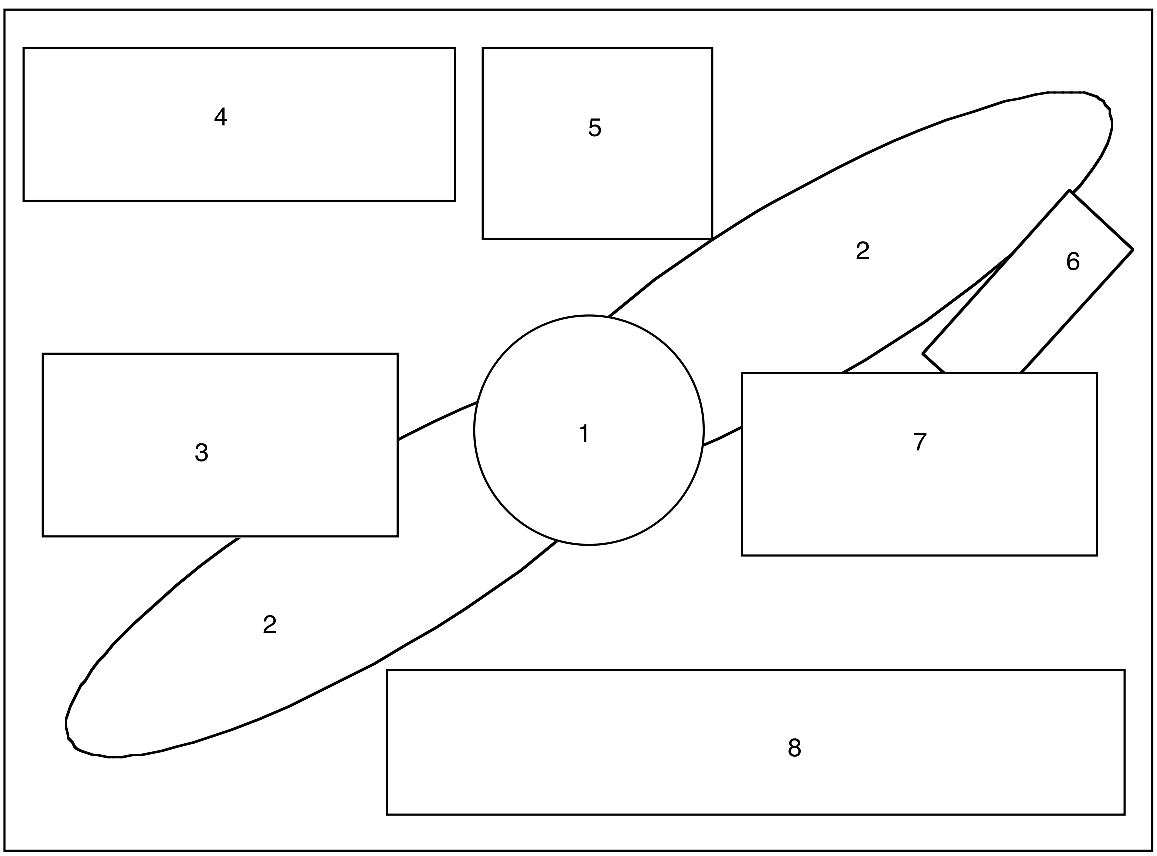

Fig. 1-1. The Nuclear Wall Chart—The sections on the chart are indicated.

found on Earth? Nuclear scientists carry out both theoretical and experimental investigations using high-energy *accelerators*, innovative *detectors*, and forefront computing facilities.

A WALK AROUND THE CHART

The Nucleus—1

The atomic nucleus consists of nucleons—protons and neutrons. Protons and neutrons are made of *quarks* and held together by the strong force generated by *gluon* exchange between quarks. In nuclei with many nucleons, the effective strong forces may be described by the exchange of *mesons* (particles composed of quark-antiquark pairs). A proton consists of two up quarks and one down quark along with short-lived constituents of the *strong force* field. A neutron is similar except that it has two down quarks and one up quark. Although scientists are convinced that nucleons are composed of quarks, a single quark has never been isolated experimentally. Energy brought into a nucleus to try to separate quarks increases the force between them. At high enough energy, the addition of energy creates new particles rather than freeing the quarks.

Chart of the Nuclides—2

The Chart of the Nuclides shows the known nuclei in terms of their *atomic number*, Z, and *neutron number*, N. Each box represents a particular nuclide and is color-coded according to its predominant *decay mode*. The so-called “magic numbers,” with N or Z equal to 2, 8, 20, 28, 50, 82, and 126 correspond to the closure of major nuclear shells (much like the atomic shells of the electrons) and enhance nuclear stability. Isotopes that have a magic number of both protons and neutrons are called “doubly magic” and are exceptionally stable.

Radioactivity—3

Atoms are *radioactive* if the protons and neutrons in the nucleus are configured in an unstable way. For low numbers of protons (*Z*), the number of neutrons (*N*) required to maintain a stable balance is roughly equal to the number of protons. For example, there are 6 protons and 6 neutrons in the nucleus of the most abundant form of carbon. For large numbers of protons in the nucleus, the repulsive electric force between protons leads to stable nuclei that favor neutrons over protons. One stable nucleus of lead contains 126 neutrons and 82 protons. A radioactive atom, lacking a proper balance between the number of protons and the number of neutrons, seeks a more stable arrangement through radioactive decay. These decays occur randomly in time, but large collections of radioactive materials have predictable mean *lifetimes*. The common decay products are named after the first three letters of the Greek alphabet—alpha (□), beta (□), and gamma (□). In an *alpha decay*, a helium nucleus escapes from a nucleus. Alpha emission reduces the number of protons by two and also the number of neutrons in the nucleus by two. *Beta decay* can proceed either by emission of an *electron* and an *antineutrino* or by emission of their antiparticles, a *positron* and a *neutrino*. Beta decay changes the number of protons and the number of neutrons in the nucleus by converting one into the other. Inverse beta decay involves the capture of an electron by a nucleus. In a *gamma decay* a high energy photon leaves the nucleus and allows the nucleus to achieve a more stable, lower energy configuration. Spontaneous *fission* of a large-mass nucleus into smaller-mass products is also a form of radioactivity.

Expansion of the Universe—4

The universe was created about 15 billion years ago in an event called the *Big Bang*. Around a microsecond after the Big Bang, the universe was populated predominantly by quarks and gluons. As the universe expanded, the temperature dropped. Eventually the universe cooled enough to allow quarks and gluons to condense into nucleons, which subsequently formed hydrogen and helium. Interstellar space is still filled with remnants of this primordial hydrogen and helium. Eventually, density inhomogeneities allowed gravitational interactions to form great clouds of hydrogen. Because the clouds had local inhomogeneities, they gave rise to stars, which collected into galaxies. The universe has continued to expand and cool since the Big Bang, and has a present temperature of only 2.7 Kelvin (K).

After the hydrogen and helium created in the Big Bang condensed into stars, nuclear reactions at the cores of massive stars created more massive nuclei up to iron in a series of nuclear reactions. Higher-mass nuclei were created at the end of the star's life in supernovae explosions. These elements were scattered into space where they later combined with interstellar gas and produced new stars and their planets. Earth and all its occupants, animate and inanimate, are the products of these nuclear astrophysical processes.

Phases of Nuclear Matter—5

One speaks of water existing in three states or phases: solid, liquid, and gas, known to us simply as ice, water, and steam. Temperature and pressure determine the phase of water molecules. Similarly, protons and neutrons exhibit different phases depending on the local nuclear temperature and density. Normal nuclei appear to be in the liquid phase. Different regions of nuclear matter include neutron stars, the early universe, a nucleon gas, or a quark-gluon plasma. Scientists study these phases by colliding beams of accelerated particles to produce extreme conditions. At this time, the quark-gluon plasma has not been identified in any experiment.

Unstable Nuclei—6

Although the Chart of the Nuclides includes about 2500 different nuclides, current models predict that at least 4000 more could be discovered. The proton and neutron "drip lines" define where nuclei with extreme ratios of neutrons-to-protons (N/Z) are expected to become so unstable that the nuclear forces will no longer allow them to form. Scientists are pushing towards making nuclei at both the proton and neutron drip lines as well as new elements at the high mass end of the Chart of the Nuclides. Element 118 (yet to be named) is the most massive element yet made artificially. Products from its alpha decay chain identified the unknown parent nucleus from only a few nuclei.

Nuclear Energy—7

Fission occurs when the nucleus of an atom divides into two smaller nuclei. Fission can occur spontaneously; it may also be induced by the capture of a neutron. For example, an excited state of uranium (created by neutron capture) can split into smaller "*daughter*" nuclei. *Fission products* will often emit neutrons because the N/Z ratio is greater at higher Z. With a proper arrangement of uranium atoms, it is possible to have the neutrons resulting from the first fission event be captured and to cause more uranium nuclei to fission. This "chain reaction" process causes the number of uranium atoms that fission to increase exponentially. When the uranium nucleus fissions, it releases a considerable amount of energy. This process is carried on in a controlled manner in a nuclear reactor, where control rods capture excess neutrons, preventing them from being captured by other uranium nuclei to induce yet another uranium fission. Nuclear reactors are designed so that the release of energy is slow and can be used for practical generation of energy. In an atomic bomb, the chain reaction is explosively rapid.

Fusion occurs when two nuclei combine together to form a larger nucleus. Fusion of low-Z nuclei can release a considerable amount of energy. This is the Sun's energy source. Four hydrogen nuclei (protons) combine in a multistep process to form a helium nucleus. More complicated fusion processes are possible; these involve more massive nuclei. Since the energy required to overcome the mutual electric repulsion of the two nuclei is enormous, fusion occurs only under extreme conditions, such as are found in the cores of stars and nuclear particle accelerators. To fuse higher-Z nuclei together requires even more extreme conditions, such as those generated in novae and supernovae. The stars are ultimately the source of all the elements in the periodic table with $Z \geq 6$ (carbon). Because fusion requires extreme conditions, producing this nuclear reaction on Earth is a difficult technical problem. It is used in thermonuclear weapons, where the fusion reaction proceeds unchecked. Controlled fusion with release of energy has occurred, but no commercially viable method to generate electrical power has yet been constructed.

Applications—8

Basic research in nuclear science has spawned benefits that extend far beyond the original research, often in completely unexpected ways. Nuclear science continues to have a major impact in other areas of science, technology, medicine, energy production and national security. Nuclear diagnostic techniques find many applications in dating archeological objects, in materials research, and in monitoring changes in the environment.